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SUMMARY

The fatigue and impact strengths are reported for diffusion bonded butt joints in IMI 318 and IMI 550 titanium alloys. Different diffusion bonding parameters were used to produce bonds with parent metal tensile strengths but different void contents. The results are related to metallographic and fractographic data.

This paper was presented at an International Conference 'Diffusion Bonding', at Cranfield, 7-8 July 1987.

LIST OF CONTENTS

1 INTRODUCTION

The combination of superplastic forming with solid state diffusion bonding (SPF/DB) has led to new manufacturing routes for airframe structures made in titanium alloys[1-3]. Significant cost and weight savings are obtainable by SPF/DB over conventional structures, but these are dependent on the ability to produce diffusion bonded joints with adequate mechanical properties. Since such joints are not always inspectable it may be necessary to rely on strict control of process parameters to obtain satisfactory and reproducible joints. A vital requirement for the success of the SPF/DB process is therefore an understanding of the factors which affect the mechanical properties of diffusion bonds. In the current work fatigue and impact strengths were determined for butt joints containing various amounts of porosity at the bond interface following diffusion bonding. (KT)

2 EXPERIMENTAL TECHNIQUE

2.1 Diffusion bonding

Butt joints were made between pairs of cylinders 12.7 mm dia × 25.4 mm long of IMI 318 (Ti-6Al-4V) and IMI 550 (Ti-4Al-4Mo-2Sn-0.5Si) alloys in an argon atmosphere, and between cylinders 25 mm dia × 25 mm of IMI 550 alloy in vacuum. The end faces of the cylinders were ground flat and normal to the cylinder axis, and the faying surfaces were given a final fine grinding to $R_a \leq 0.4$ µm. This was achieved by dressing the grinding wheel with a diamond tipped tool prior to each cut. During the programme the workshop grinding fluid was changed from Dromus slurry to filtered Ultragrind-S compound. Use of the latter results in a more consistent surface roughness since the presence of deep grinding grooves caused by recirculation and entrapment of debris between the grinding wheel and workpiece was avoided. The specimens were degreased in acetone before being placed in the bonding apparatus with the faying surface grinding directions normal to one another.

Two sets of bonding parameters were selected for joining the 12.7 mm dia specimens, of both alloys, in gettered argon; these were ½ hour at 925°C under 0.52 MPa pressure (to give 'high' void levels at the interface) and 2 hours at 950°C under 0.69 MPa (to give 'low' void levels). Earlier work[4,5] showed that parent metal tensile properties were obtained for these conditions. The 25 mm dia specimens of IMI 550 alloy were diffusion bonded in vacuum for 2 hours at 950°C under pressures of 1.2, 2.0, 2.8 and 6.0 MPa (to provide at least some specimens with no voids). In all cases it was necessary to slow cool the

specimens in the furnace. Parent metal control specimens were subjected to the same stress and thermal cycles to enable direct comparisons of mechanical properties to be made.

2.2 Examination and testing of joints

Each 12.7 mm dia specimen was machined to give either a Rolls-Royce rotating bend fatigue test piece or a Hounsfield impact test piece with the bond-line at the middle of the gauge length. In addition some ¼ in BSF tensile test pieces were made; after testing these were sectioned to enable void levels to be measured (fracture occurred away from the bond interface). The 25 mm dia IMI 550 alloy specimens were cut axially into quadrants, which were machined to produce one tensile and two impact test pieces with one metallographic specimen for each bonding condition. After examination the metallographic specimens were machined to give Hounsfield impact test pieces. One of the metallographic specimens was also used for microhardness and electron probe microanalysis (EPMA) (for oxygen) surveys across the bond interface. Fractographic examination by optical and scanning electron microscopy (SEM) was made of broken test-piece fracture surfaces.

3 RESULTS

3.1 Metallography

Micrographs of bonds in IMI 550 alloy containing 'high', 'low' and zero optically visible void levels (≥1 μm) are shown in Fig 1; quantitative values determined for all the joints examined are listed in Table 1. It is apparent that the difference in surface roughness between Run Nos. 9 and 71 had a greater effect on the subsequent void level than did the bonding parameters. In general, however, the porosity content was lower for both alloys when bonded for 2 hours at 950°C under 0.69 MPa pressure compared to ½ hour at 925°C under 0.52 MPa. No voids were detected in the 25 mm dia IMI 550 alloy joints at any of the higher pressures used. No changes in hardness or oxygen content were detected during surveys across the interface of the specimen diffusion bonded under 1.2 MPa pressure.

3.2 Mechanical testing

The S/N fatigue test curves for 'high' and 'low' void level conditions are shown in Figs 2 (IMI 318) and 3 (IMI 550). Data points for test pieces which did not fail after 10^7 cycles and were retested at higher stresses are included, but annotated differently. In cases where fracture revealed that the bond line was

offset from the middle of the gauge length, the joint thus having a larger cross-sectional area and experiencing a lower stress than planned, the points are accompanied by a downward pointing arrow. The fatigue strengths for both alloys diffusion bonded for 2 hours at 950°C under 0.69 MPa pressure were the same as those of the parent metal controls (Figs 2a and 3a). The fatigue strength of the IMI 318 alloy diffusion bonded for ½ hour at 925°C under 0.52 MPa pressure (Fig 2b) was 30% lower than that of the corresponding controls. There was more scatter in the data for this S/N curve than any of the others; this may have been due to the grinding technique used for these test pieces (Dromus slurry lubricant), but it is more likely to be due to the void level being such that the chance of a pore cluster being present at or near the test piece surface was less probable than that in the case of the IMI 550 alloy which had a higher void content. The fatigue strength of the IMI 550 test pieces diffusion bonded using the 'high' void level condition was 30% lower than that of the controls.

The Hounsfield impact values obtained for the 12.7 mm dia specimens (Fig 4) show that the average toughness of joints diffusion bonded in the 'high' void level condition were only 12% (IMI 318) and 14% (IMI 550) of those of the corresponding control test pieces. The toughness of joints diffusion bonded in the 'low' void level condition were 49% (IMI 318) and 25% (IMI 550) of the control test-piece values. When the bonding pressure was increased (for 25 mm dia IMI 550 alloy bar diffusion bonded in vacuum) no voids were detected (Table 1) and impact values generally increased (Fig 5) irrespective of pressure, but there was considerable scatter ranging from 39% to 98% of the mean parent metal control value. It was difficult to ensure that the root of the test-piece notch coincided exactly with the bond interface so the offset distance between them is included in Figs 4 and 5; the offsets for two test pieces marked (?) are unknown since the fracture was completely ductile. Since their toughness was the same as that of the parent metal it is likely that the offset was sufficiently large for fracture to have occurred completely in the parent metal. There is no obvious correlation between the offset distances and impact values; the toughness would be expected to increase with increasing area of non-interfacial fracture.

3.3 Fractography

Examination of the fatigue test-piece fracture surfaces showed that the surfaces of specimens prepared by grinding with Dromus slurry lubricant contained some deep grinding grooves. However, since cracks usually initiate at the surface of rotating bending test pieces, and no sub-surface initiation sites were detected, it is unlikely that the fatigue lives were affected.

When the impact test-piece notch tip was offset from the bond interface, after initiation from the notch the crack mode changed from ductile to planar fracture along the bond interface as soon as it encountered it (Fig 6a). Although the fracture at the interface is macroscopically brittle closer examination shows that, microscopically, it is predominantly ductile (Fig 6b) with some very small (<2 μm) voids present. The area between the notch and the step to the bond interface is completely ductile (Fig 6c).

4 DISCUSSION AND CONCLUSIONS

Comprehensive details of the RAE diffusion bonding apparatus, bonding technique and experimental results have been reported elsewhere[4,6].

Micro-discontinuities left at the interface of incompletely diffusion bonded joints are arranged in the plane of contact and are linked by grain boundaries; this microstructure is favourable to the spread of cracks along the interface[7].

It is well known that the tensile strength of diffusion bonded joints is unaffected by the presence of up to 20% length of voids at the interface [*eg* Ref 8], and that elongation and reduction of area values are more sensitive to these voids if failure occurs at the bond-line [*eg* Refs 4 and 5]. No reports of the effect of measured void levels on the fatigue strength of titanium alloys have hitherto been reported but several authors have shown that fatigue strengths as good as or better than that of the parent metal are obtainable if the correct diffusion bonding parameters are used[9-13]. Rotating bend type tests, such as that used in the current investigation, are probably inferior to the push-pull type since the nature of the stress distribution is such that the chance of crack initiation from an internal pore is lower in the former. Gunderson *et al*[10], who determined the fatigue strengths (push-pull) of five different areas of a large (1372 mm dia) diffusion bonded Ti-6Al-4V rotor hub, found that parent metal fatigue strength was achieved in four of these areas. In the fifth area insufficient plastic deformation at the bond-line resulted in sub-surface crack initiation and reduced fatigue strength; it was concluded that small single voids were insignificant but clusters of voids markedly reduced fatigue lives. The results of the current work support this conclusion.

Nearly all work reported on the relationship between interface voids and the impact strength of solid state diffusion bonded joints in titanium alloys has originated from the USSR. These have shown that not only is the impact test extremely sensitive to the presence of even submicroscopical pores (<1 μm), but

that the impact strength is also affected by microstructural and crystallographic textural inhomogeneities in the joint region. Comprehensive investigations on conventionally (*ie* creep controlled) diffusion bonded joints in VT6 (Ti-6Al-4V) alloy were carried out by Gel'man *et al*[14-18]. These workers demonstrated that the relative impact strength of bond/parent metal, at various stages of joint formation, could be correlated with characteristic features revealed by metallographic[16] and electron fractographic[15] examinations. In the current work the toughness of joints with a few optically visible voids was only 49% (IMI 318) and 25% (IMI 550) of that of the parent metal. For conditions where none of these voids were visible the toughness varied between 39% and 98% of the parent metal (IMI 550). However, SEM examination revealed the presence of very small voids (<2 μm) in the latter, indicating that impact toughness is an extremely sensitive test of diffusion bond quality.

Recent work in the USSR has been concentrated on the 'forced deformation' technique in which the diffusion bonding process is accelerated by controlling the strain rate[12,17-20]. The method has the advantage of being less dependent on the bonding parameters, including temperature, and on the flow stresses of the materials being joined. It also allows control of the mechanism of plastic strain, the intensity of work hardening and other processes accompanying joint formation. For example, the residual strains accompanying bonding can be minimised by cyclic application of the load below the yield stress; this confines the plastic deformation to the faying surface asperities, and is especially useful in cases where the alloy is superplastic. Karakozov *et al*[17-19] measured the relative impact strengths (bond/parent metal) of joints made in VT6 alloy over a wide range of bonding temperatures and strain rates. It was found that when 5% plastic strain was applied, for each bonding temperature, as the strain rate was increased the toughness rose to a maximum and then fell. Relative impact strengths of 80% were only achieved over limited ranges of temperature and strain rate. The optimum values, for which parent metal impact strength was almost achieved, were 960°C and $2.5 \times 10^{-4}\ s^{-1}$. In order to explain this behaviour Karakozov *et al*[21] measured the crystallographic texture of sections cut at 15-30 μm intervals over a total distance of 0.5 mm from the bond interface. These showed that for the condition at which maximum impact strength was obtained the texture was homogeneous across the joint and of the same intensity as that of the parent metal. For all other bonding conditions, the impact strength fell with increasing inhomogeneity of texture across the joint interface. It was speculated that the optimum condition occurred when the rates of strain hardening

and recovery processes in the joint region balanced. In VT6 alloy under superplastic conditions intensive grain boundary sliding causes changes in the texture in the contact zone and parent metal impact strength is not achieved. With other less notch-sensitive alloys the situation is different[22].

Various means of improving the impact toughness of diffusion bonded joints in titanium alloys have been attempted, with varying degrees of success. These include post-bond annealing at the bonding temperature[11,15], thermal cycling through the β-transus temperature[23], the simultaneous application of ultrasound[24], the introduction of interlayers of β-stabilising elements[25] and transient liquid phase diffusion bonding (LPDB) with Cu[26,7]. Impact toughness as high as or almost as high as that of the parent metal has been achieved by two of these techniques[23,24], and parent metal fatigue strengths were obtained by LPDB (rotating bend[26], and push-pull, $R = 0$[7]).

In summary, it is clear that the impact test is by far the most sensitive test of diffusion bond quality, being sensitive to the presence of submicroscopic pores (<1 μm). However, the absence of pores in a bond does not itself guarantee parent metal impact strength since this is also affected by microstructural and textural inhomogeneities in the joint region. Fatigue strength is reduced when clusters of pores are present, and is, in turn, a much more sensitive test than the tensile test. In the current work the relative impact strengths of joints which had parent metal tensile and fatigue strengths were only 49% (IMI 318) and 25% (IMI 550) (Fig 7).

Acknowledgments

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TABLE 1

NUMBER AND SIZE OF VOIDS AT DIFFUSION BOND INTERFACES IN IMI 318 AND IMI 550

Alloy	Bar Diameter mm	Run No	Grinding		Diffusion Bonding Conditions				Comp Dcin	Number of Voids in Length Ranges (μm)								Total length		Total area/length *
			Lubricant	Finish μm CLA	Time h	Temp. °C	Pressure MPa	Environment	%	≤2	2.5 -5	5.5 -10	10.5 -15	15.5 -20	20.5 -25	>25 No	>25 Size	μm	%	mm x 10^{-6}
IMI 318	12.7	9	Dromus	0.10/0.12	1/2	925	0.52	Argon	1.9	5	9	2	0	0	0	1	52	107^{Δ}	3.2 (1.6)	$283^{\square}$ (31)
		71		0.50/0.55$^{\phi}$	2	950	0.69		5.1	4	39	21	12	3	2	1	65	666	8.8 (7.9)	$326^{\square}$ (261)
		95	Ultragrind-S	0.27/0.20					6.6	32	24	4	2	0	1	0	-	166	2.1	70
IMI 550		5	Dromus	0.37/0.25	1/2	925	0.52		1.5	16	20	11	5	2	2	1	152	479^{Δ}	14 (9.5)	$812^{\square}$ (352)
		116	Ultragrind-S	0.22/0.27					1.3	50	35	18	8	0	0	1	32	472	6.1 (5.7)	$166^{\square}$ (145)
		67	Dromus	0.32/0.32	2	950	0.69		2.1	8	28	12	10	4	1	1	27	439	5.9	249^{xx}
		81	Ultragrind-S	0.27/0.27					2.9	19	20	9	2	0	0	0	-	168	2.4	62^{xx}
		82		0.25/0.30			1.03		5.1	15	11	3	1	0	0	0	-	85	1.2	27^{xx}
	50	GCA/B5		0.38/0.25			1.2	Vacuum	5.0	0	0	0	0	0	0	0	-	$0^{\dagger}$	0	0
		GCA/B2		0.23/0.36			2.0		8.8	0	0	0	0	0	0	0	-	$0^{\dagger}$	0	0
		GCA/B7		0.26/0.29			2.8		11.6	0	0	0	0	0	0	0	-	$0^{\dagger}$	0	0
		GCA/B3		0.18/0.35			6.0		24.0	0	0	0	0	0	0	0	-	$0^{\dagger}$	0	0

* reported this way in earlier work[4]
† there may be some isolated small voids; not measured because of difficulty in identifying bond interface (see text)
ϕ surface finish above specification (0.4 μm maximum)
□ result significantly affected by presence of one very large void; figure in brackets gives figure obtained when this large void was ignored
Δ only one half section of test piece examined
xx bond line near fracture

REFERENCES

No.	Author	Title, etc
1	E.D. Weisert G.W. Stacher	Fabricating titanium parts with SPF/DB process. *Metal Progress*, **111**, 33 (1977)
2	G.W. Stacher E.D. Weisert	Concurrent superplastic forming/diffusion bonding of B-1 components. AGARD-CP-256, Advanced Fabrication Processes, Paper 15 (1978)
3	D. Stephen S.J. Swadling	Diffusion bonding in the manufacture of aircraft structure. AGARD-CP-256, Advanced Joining of Aerospace Materials, Paper 2 (1985)
4	T.S. Baker P.G. Partridge	Tensile properties and fracture mode of diffusion bonds in Ti-6Al-4V and Ti-4Al-4Mo-2Sn-0.5Si alloy bars. RAE Technical Report 83015 (1983)
5	T.S. Baker P.G. Partridge	Properties of diffusion bonded butt joints in Ti-6Al-4V and Ti-4Al-4Mo-2Sn-0.5Si (IMI 550) alloys. *Proc. 5th Int. Conf. on Titanium*, Munich, **2**, 861, 10-14 September 1984
6	T.S. Baker	Fatigue and impact strengths of diffusion bonded butt joints in Ti-6Al-4V and Ti-4Al-4Mo-2Sn-0.5Si (IMI 550) alloys. RAE Technical Report in preparation (1987)
7	J. Fielding C.H. Bott	Diffusion bonding. Proc. Conf. Advances in Welding Processes, UK Welding Inst., p72, 14-16 April 1970
8	A.A. Gel'man A.A. Kotel'nikov N.I. Kolodkin	Effect of diffusion bonding variables on structure and properties of the bonded $\alpha+\beta$ titanium alloy. *3rd Int. Conf. on Titanium*, Moscow, **2**, 1209, 18-21 May 1976
9	R.J. Rehder D.T. Lovell	Process development for diffusion welding Ti-6Al-4V alloy. *Welding Journal*, **49**, 5, Research Supplement 213-s (1970)

REFERENCES (continued)

No.	Author	Title, etc
10	A. Gunderson H.L. Gegel S.R. Lyon	Fatigue behaviour of diffusion bonded Ti-6Al-4V having very small defects. *Proc. 2nd Int. Conf. on Titanium*, Cambridge, Mass., 1, 649, 2-5 May 1972
11	A.A. Gel'man	Special features of the formation of joints in the diffusion bonding of two-phase titanium alloys. *Welding Production*, **28**, 5, 23 (1981)
12	V.N. Zamkov	Welding and brazing of titanium alloys - critical review. *Proc. 5th Int. Conf. on Titanium*, **2**, 771, 10-14 September 1984
13	E.S. Karakozov S.S. Vasil'eva S.V. Ivanov	Effect of the thermal cycle on characteristics of cyclic cracking resistance of titanium alloys and diffusion bonded joints in them. *Welding Production*, **32**, 1, 41 (1985)
14	A.A. Gel'man *et al*	Special features of the failure of welded joints in VT6 alloy. *Welding Production*, **30**, 2, 22 (1983)
15	A.A. Gel'man N.M. Semenova O.A. Mozolevskaya G.V. Golubeva	Special features of the structure of diffusion bonded joints in titanium alloys. *Russian Metallurgy*, **33**, 3, 80 (1980)
16	A.A. Gel'man *et al*	Effect of defects on the impact toughness of welded joints in VT6 alloy. *Welding Production*, **32**, 10, 15 (1985)
17	E.S. Karakozov A P. Ternovskii V.E. Tarlavskii	Diffusion welding of the VT6 titanium alloy with constrained deformation. *Automatic Welding*, **32**, 4, 20 (1979)
18	E.S. Karakozov A.P. Ternovskii	Optimisation of the thermal and strain cycle in pressure welding without preheating. *Welding Production*, **28**, 5, 33 (1981)

REFERENCES (concluded)

No.	Author	Title, etc
19	E.S. Karakozov A.P. Ternovskii	Forced deformation welding gives better joint control. *Welding and Metal Fabrication*, **49**, 10, 602 (1981)
20	V.S. Tarlavskii A.I. Potapov	Forced deformation welding produces precision joints. *Welding and Metal Fabrication*, **50**, 1/2, 37 (1982)
21	E.S. Karakozov Yu.A. Perlovich M.G. Isaenkova	Heterogenity of texture in the zone of a diffusion welded joint in VT6 titanium alloy. *Automatic Welding*, **34**, 2, 19 (1981)
22	A.A. Gel'man N.I. Kolodkin A.A. Kotel'nikov A.V. Bashurin	Optimum parameters for the diffusion welding of titanium alloys with different phase compositions. *Automatic Welding*, **30**, 4, 41 (1977)
23	F. Persiani G.P. Cammareta	Impact strength of Ti-6Al-4V joints diffusion bonded at low contact pressure. *Metall. Ital.*, **77**, 6, 423 (1985)
24	A.A. Kotel'nikov O.P. Bogdanov A.V. Bashurin S.S. Varaks	Titanium alloys diffusion welded with ultrasound applied. *Automatic Welding*, **31**, 1, 40 (1978)
25	K.E. Charukhina V.I. Grigor'evskii	Alloying of the joint zone in the diffusion bonding of titanium alloy OT4. *Welding Production*, **26**, 10, 16 (1979)
26	K.R. Perun	Diffusion welding and brazing of titanium 6Al-4V process development. *Welding Journal*, **46**, 9, Research Supplement 385-s (1967)

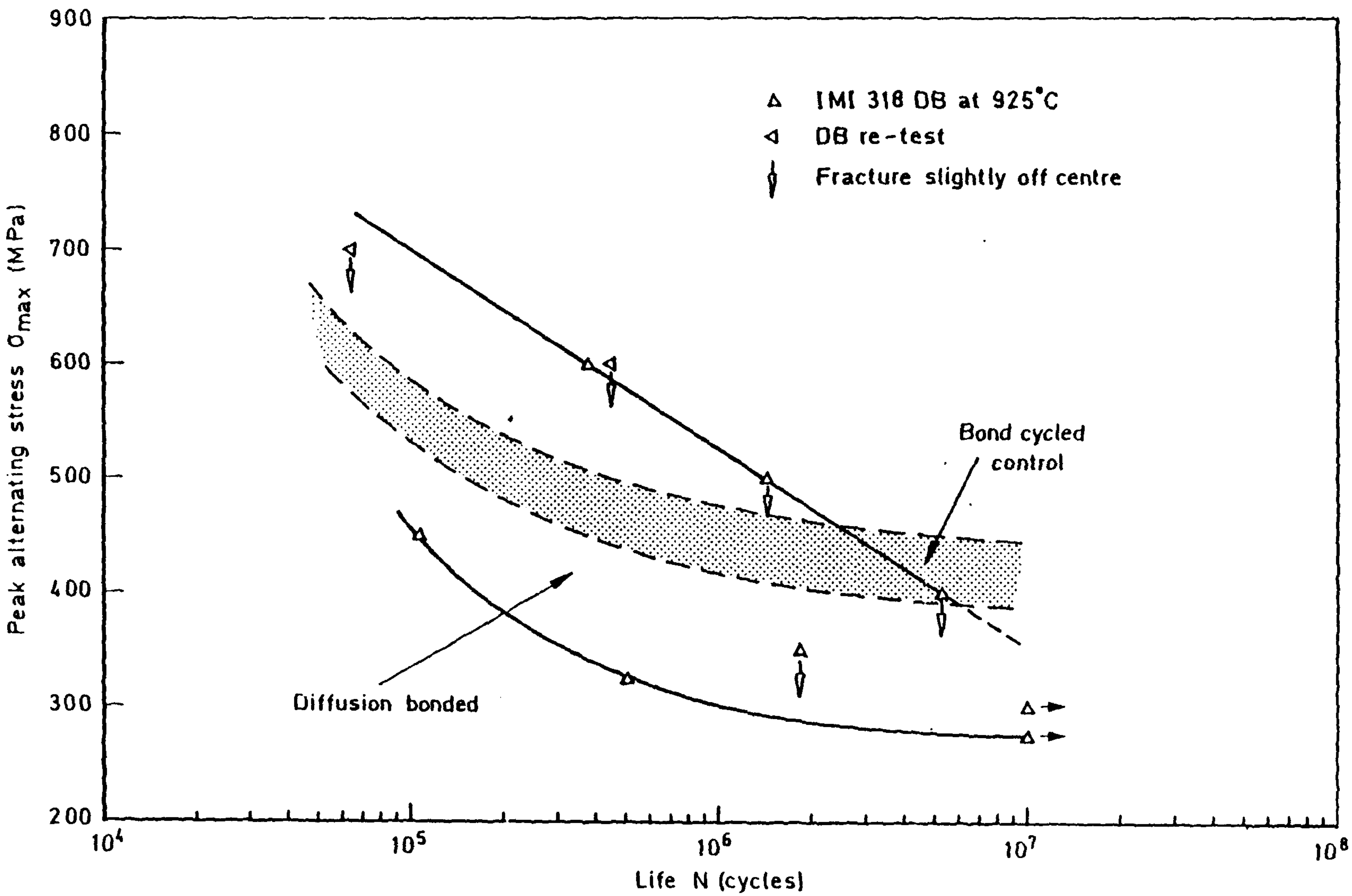

Fig 2b Fatigue strength of IMI 318 diffusion bonded for 1/2 h at 925°C, under 0.69 MPa pressure (R = -1)

Fig 3a

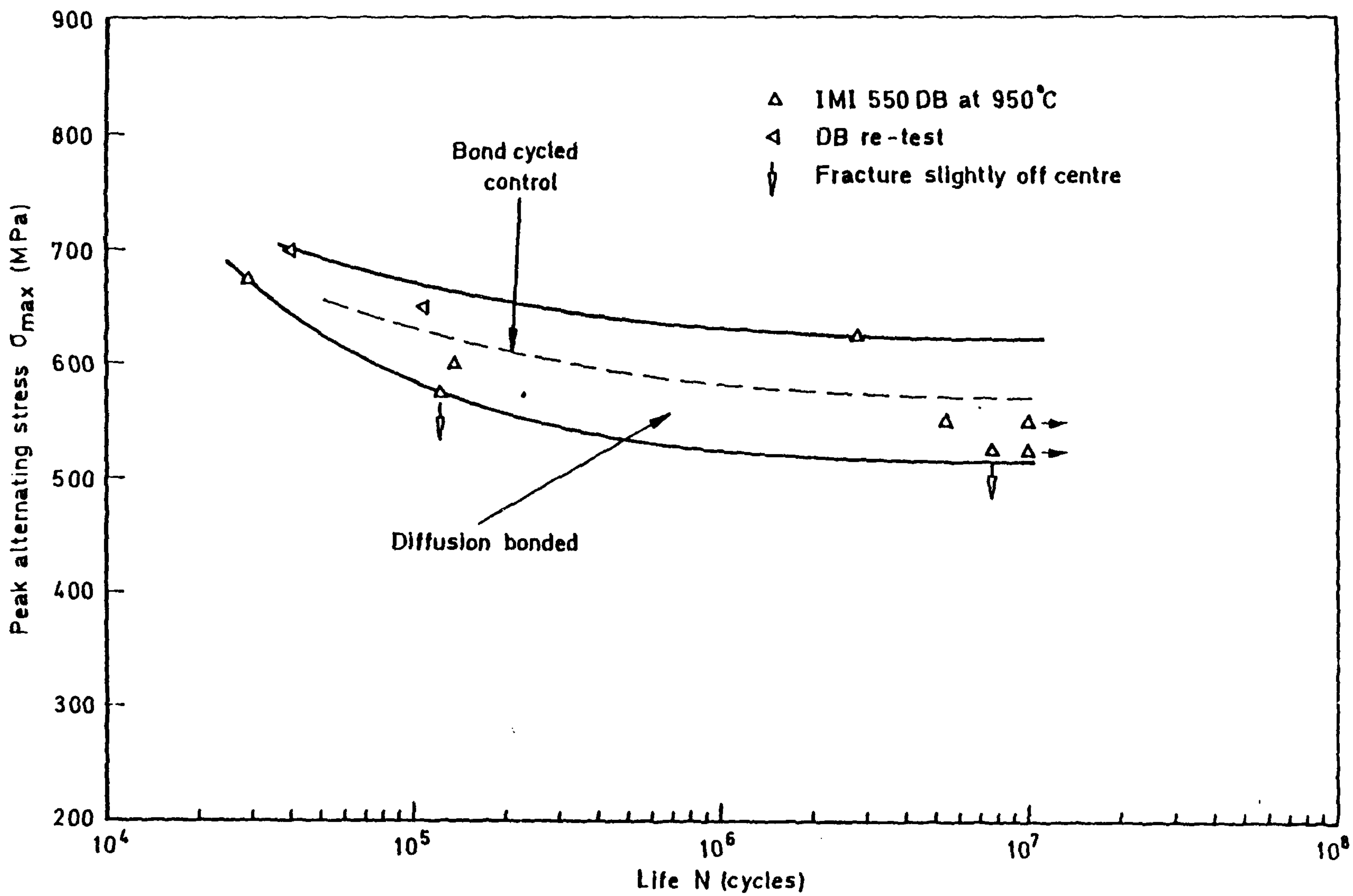

Fig 3a Fatigue strength of IMI 550 diffusion bonded for 2 h at 950°C, under 0.69 MPa pressure (R = -1)

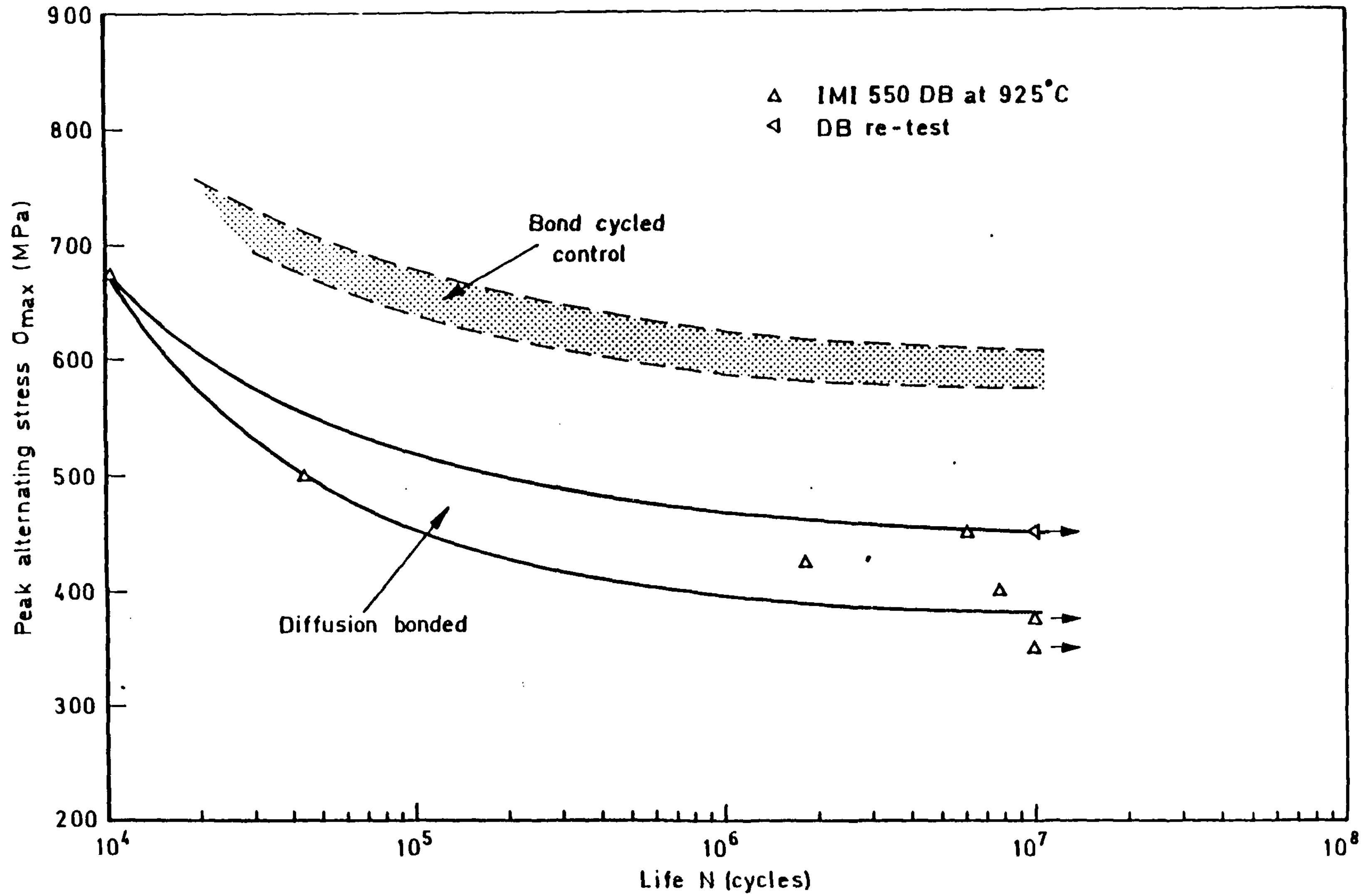

Fig 3b Fatigue strength of IMI 550 diffusion bonded for 1/2 h at 925°C, under 0.52 MPa pressure (R = -1)

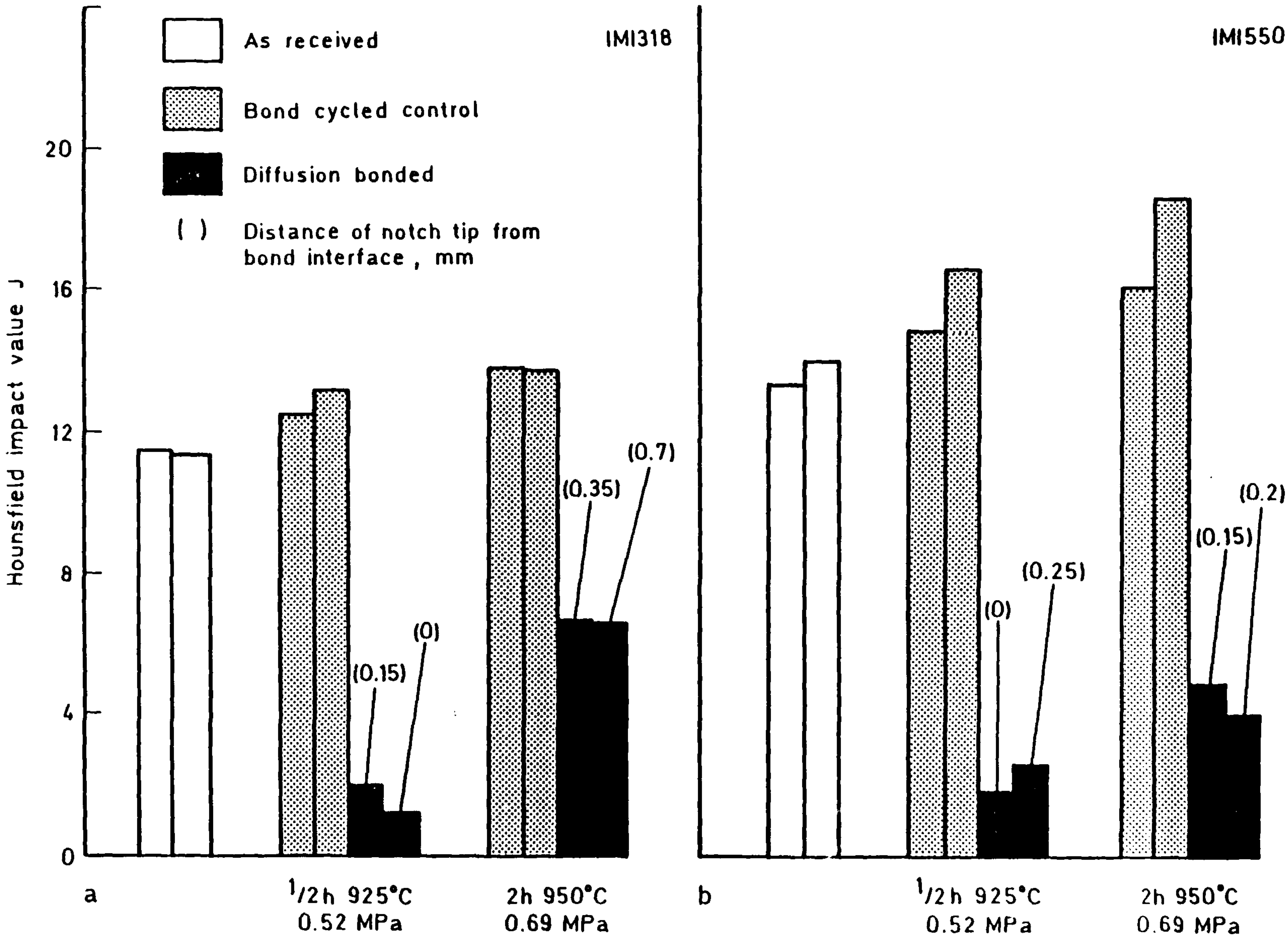

Fig 4 Impact strength of joints in diffusion bonded 12.7 mm dia bar:
(a) IMI 318; (b) IMI 550 alloy

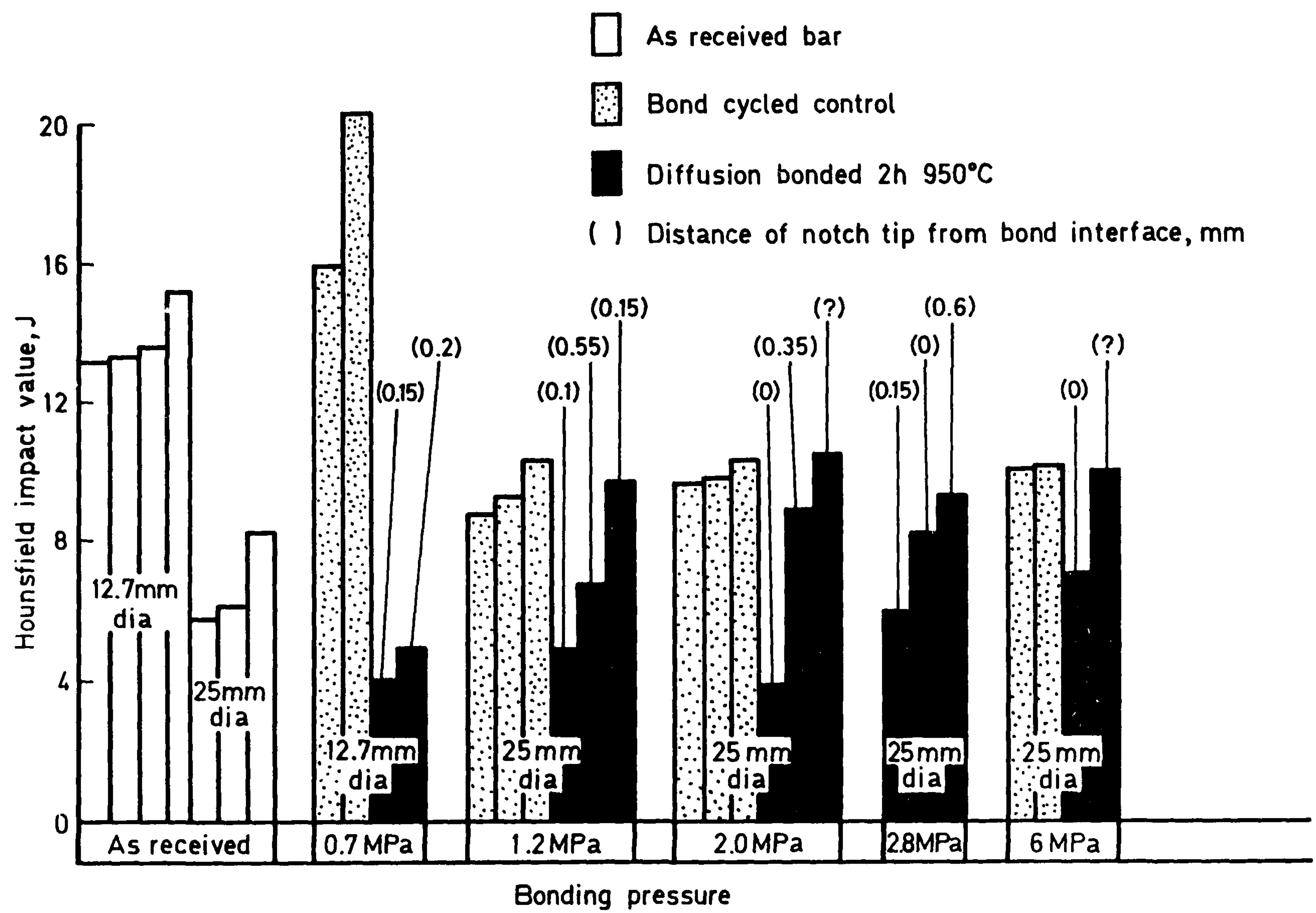

Fig 5 Impact strength of joints in IMI 550 alloy - diffusion bonded for 2 h at 950°C at various pressures

Fig 6a-c

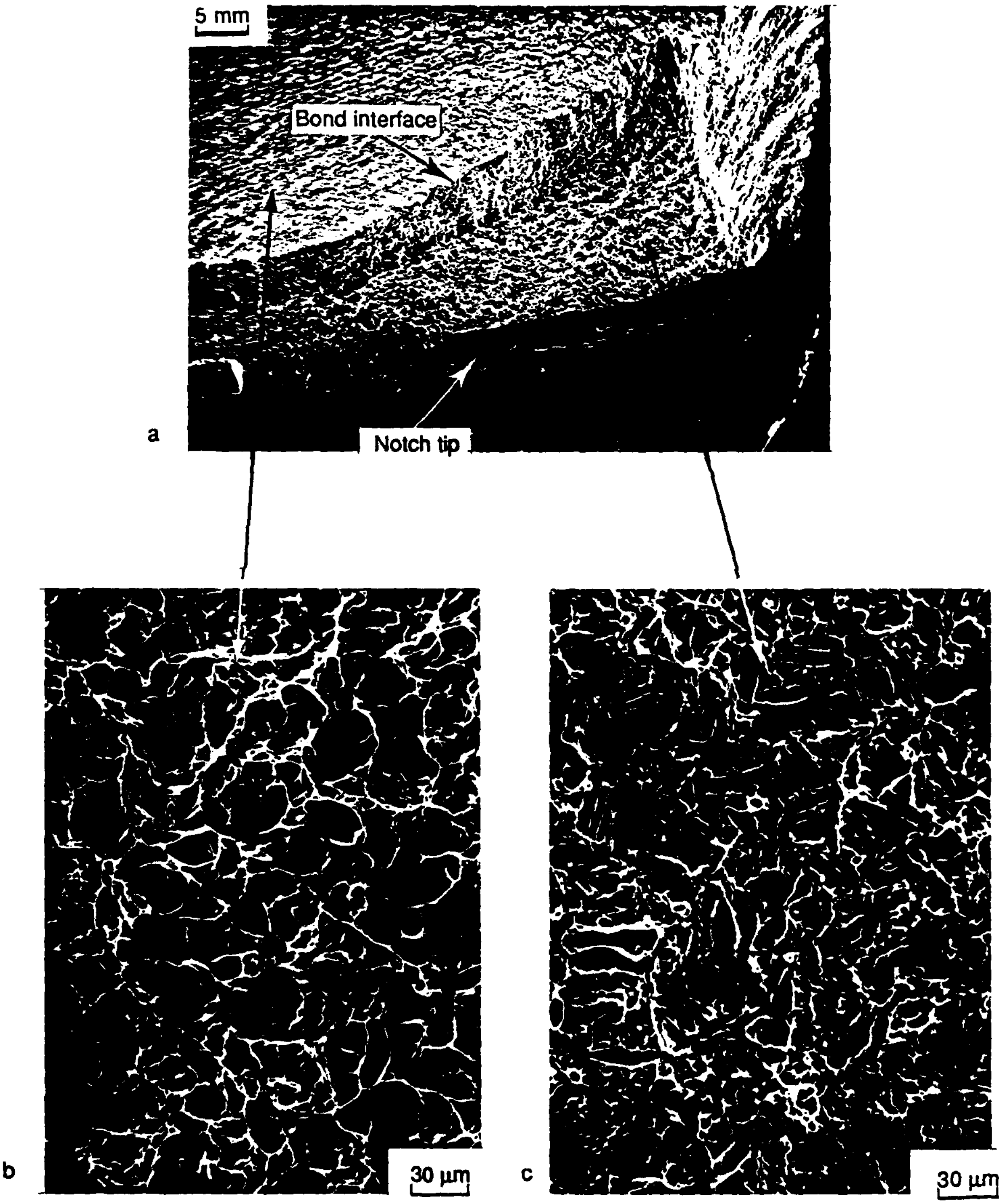

Fig 6 Fracture surface of IMI 550 alloy impact test piece: (a) general view; (b) at bond interface; (c) in parent metal region

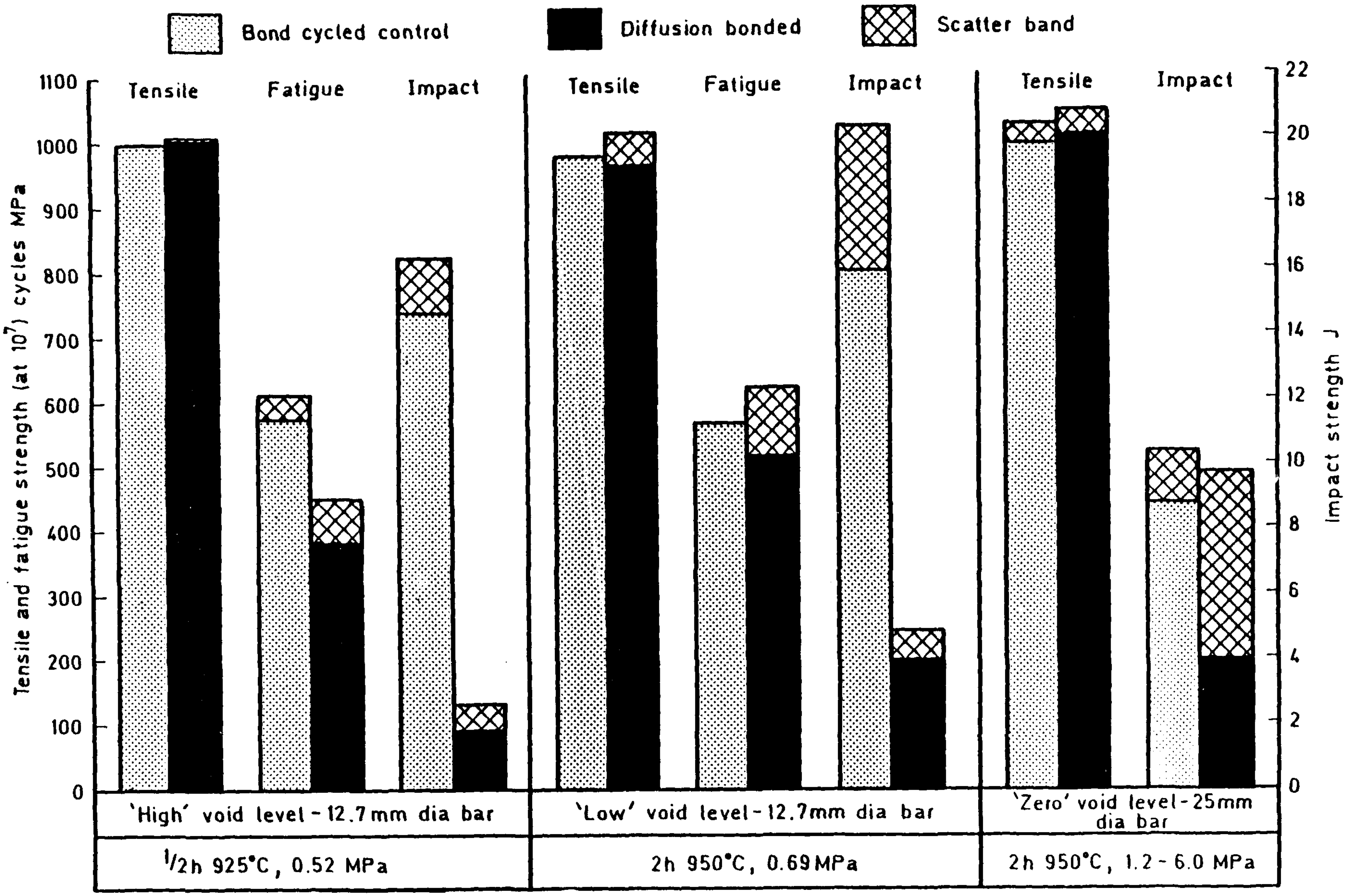

Fig 7 Effect of bonding parameters, and void level, on the tensile, fatigue and impact strengths of IMI 550 alloy butt joints

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17. Abstract

The fatigue and impact strengths are reported for diffusion bonded butt joints in IMI 318 and IMI 550 titanium alloys. Different diffusion bonding parameters were used to produce bonds with parent metal tensile strengths but different void contents. The results are related to metallographic and fractographic data.

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